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Group delay and dispersion tailoring in nonadiabatic tapered fibers

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ABSTRACT

The dispersion profile of a nonadiabatic tapered singlemode fiber is characterized and dynamically tuned. Its group delay and dispersion parameters are measured and compared to those of a standard singlemode fiber. The dispersion profile can be tuned by introducing a phase shift through mechanical stretching. Coarse tuning is also obtained by varying the surrounding medium of the tapered fiber. Dispersion values up to 700 ps/nm·km in nonadiabatic tapered fibers are obtained for the first time. Dynamic tuning exposed here can be very useful in applications such as nonlinearities or soliton generation.

1. Introduction

Chromatic dispersion is one of the limiting effects in optical communications systems. It broadens optical pulses leading to degradation in the quality of the system, not only increasing the noise level in analogical systems but also inducing Inter Symbol Interference (ISI) in digital systems [1,2]. The latter reduces the bitrate-distance product, this is the amount of data that can be transmitted per time and space through optical links. Besides, several functionalities such as nonlinear generation [3], broadband optical parametric gain [4] and soliton generation [5] are highly dependent on the dispersion characteristics of the device. Therefore, an accurate management of the chromatic dispersion profile of devices and systems is required. Chromatic dispersion can be split into material dispersion and waveguide dispersion. Dispersion tailoring is usually performed by varying the structural and geometrical parameters of the device [6–10], which allows for more control on their response as opposed to material engineering which usually requires the fabrication of different devices using different materials.

Tapered fibers consist of a narrow waist located between two transition regions [11]. This structure is obtained by exposing a standard single-mode fiber to a heating and stretching process [12]. Depending on the length of the transition region two types of tapered fibers can be distinguished: in adiabatic tapers these regions are long enough to allow the fundamental mode to propagate through the taper without experiencing any mode coupling; however, non-adiabatic tapers are abrupt and the fundamental mode experiences higher-order mode coupling in the tapered regions. Biconical tapered fibers have been employed in several functionalities such as sensing [13], super-continuum generation [14] and pulse shaping [15]. The great development of tapered fibers lies in the simplicity in which conventional propagation characteristics of standard optical fibers can be modified.

In this context, dispersion tailoring in adiabatic tapered fibers have been demonstrated by the modification of geometrical parameters such as the waist diameter [16] and structural parameters such as the refractive index of the outer medium [17,18]. However, if the tapered fiber is immersed in different liquids to modify its surrounding medium, a very careful cleaning must be carried out after the measurements in order to return to the starting state of the taper. Also, dispersion engineering just by means of the variation of geometrical parameters in the manufacturing process presents a more static behavior. This paper proposes using non-adiabatic tapered fibers to perform dynamic chromatic dispersion tailoring in a wide bandwidth by mechanically stretching the fiber. This stretching introduces a controlled phase shift which affects the spectral response, varying the dispersion characteristics of the fiber in a simple and dynamic way. Further control on the dispersion response is demonstrated by modifying the refractive index (RI) of the outer medium without immersing the tapered fiber in fluids.

2. Principle of operation

Fig. 1 shows the profile of a non-adiabatic biconical tapered fiber with waist of diameter ρ and length L_W located between two transition regions of length T_t. Most of the energy from the fundamental mode that is injected through the input taper splits

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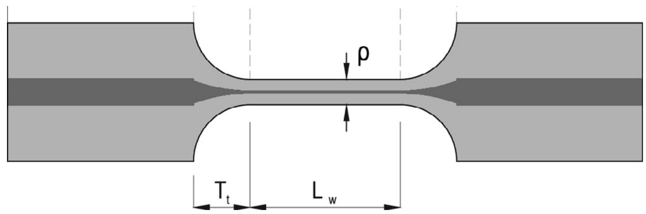

Fig. 1. Biconical tapered fiber.

into the cladding fundamental mode and a higher-order cladding mode, described by its effective refractive indexes n_{eff1} and n_{eff2}, respectively. These modes propagate through the waist experiencing different effective propagation distances that depend on their mode effective indexes [19].

These modes interfere at the output transition region, leading to an interference fringe pattern in the frequency domain, similar to that of a Mach–Zehnder interferometer (MZI). The expression of the phase delay follows [15]

$$\varphi(\lambda) \sim \sin\left(\frac{2\pi}{\lambda} \cdot L_w \cdot (n_{eff1} - n_{eff2}) + \varphi_0\right) \tag{1}$$

where $\Delta n_{eff} = n_{eff1} - n_{eff2}$ accounts for the difference between the effective indexes of the waist modes, λ is the vacuum wavelength and φ_0 is the initial phase. According to this expression, variations in waist length [20] and effective indexes [21,22] of the modes directly influence the spectral response of the taper. Group delay and chromatic dispersion are related to the phase by the following relations

$$\tau_g = \frac{\partial\varphi}{\partial\omega} \sim \frac{L_w}{c} \cdot \Delta n_{eff} \cdot \cos\left(\frac{2\pi}{\lambda} \cdot L_w \cdot n_{eff} + \varphi_0\right) \tag{2}$$

$$D = \frac{d}{d\lambda}\left(\frac{1}{\tau_g}\right) \sim \frac{-2\pi c}{\lambda^2} \cdot \tan\left(\frac{2\pi}{\lambda} \cdot L_w \cdot \Delta n_{eff} + \varphi_0\right) \cdot \sec\left(\frac{2\pi}{\lambda} \cdot L_w \cdot \Delta n_{eff} + \varphi_0\right) \tag{3}$$

Thus, by varying the phase difference of the interference pattern, group delay and chromatic dispersion of the tapered fiber can be modified. According to Eq. (2), maximum values in the phase transference function become minimum values in the group delay profile and vice versa. Please note that this expression accounts for the effect of the tapered fiber but not for the effect of the waveguide and material of the optical fiber. For the wavelength spans considered in the experimental section, the waveguide and material dispersion components should follow a linear slope. In addition, by assuming that only two modes interfere we are neglecting the effect of the rest of modes. They will show up in the experiments as differences from the ideal cosine described in Eq. (2). Eq. (3) shows how dispersion becomes zero at local maximums in the group delay and maximum absolute values at the local minimums. Please note how, according to Eq. (3), one would expect the maximum and minimum values to become positive and negative infinites, respectively. This is because Eq. (2) considers that the interference between the two modes is perfect, which is far from true in an experimental environment. To sum up, the equations provided in this section are accurate enough to estimate the position of the maximum and minimum values, as well as to predict tendencies when tuning the different parameters. However, they do not provide an accurate representation of the experiments.

Fig. 2 shows the transmission response of a non-adiabatic tapered fiber manufactured using a standard single mode fiber at 1550 nm, Corning SMF 28e+, with parameters $T_t = 1$ mm, $L_W = 13$ mm and $\rho = 18$ µm, obtained using an Optical Network Analyzer (ONA) from Advantest. Frequency modulation and fiber index were set to 3 GHz and 1.45, respectively. The length of the whole section of fiber is $L = 79.5$ cm. As can be seen in its fringe pattern, the taper presents a free spectral range (FSR) value of 8.2 nm and a visibility of approximately 5 dB. The taper was set in a translation stage by fixing its sides using two drops of glue in contact with the cladding. Group delay and chromatic dispersion characteristics of the tapered fiber as a function of wavelength were measured by using the ONA with the same configuration parameters, and the obtained results are illustrated in Fig. 3. A standard single-mode fiber (SSMF) section of fiber with the same characteristics as the tapered one and with the same total length L as the tapered segment was also characterized for comparison purposes in a 40 nm bandwidth centered at 1550 nm. As can be seen, inserting the taper clearly modifies the conventional propagation characteristics of the standard fiber, resulting in a periodic behavior in its group delay response. The periodicity of the group

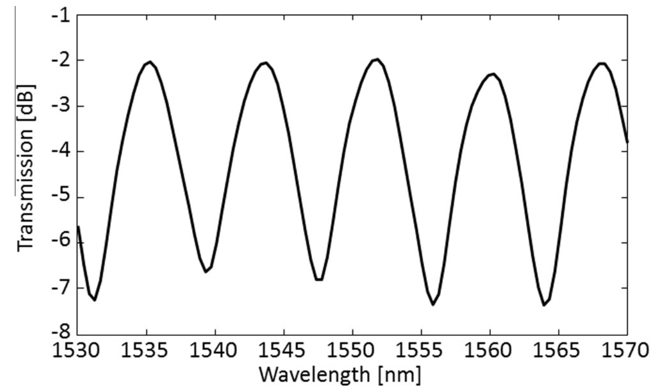

Fig. 2. Experimental transmission response of a biconical tapered fiber.

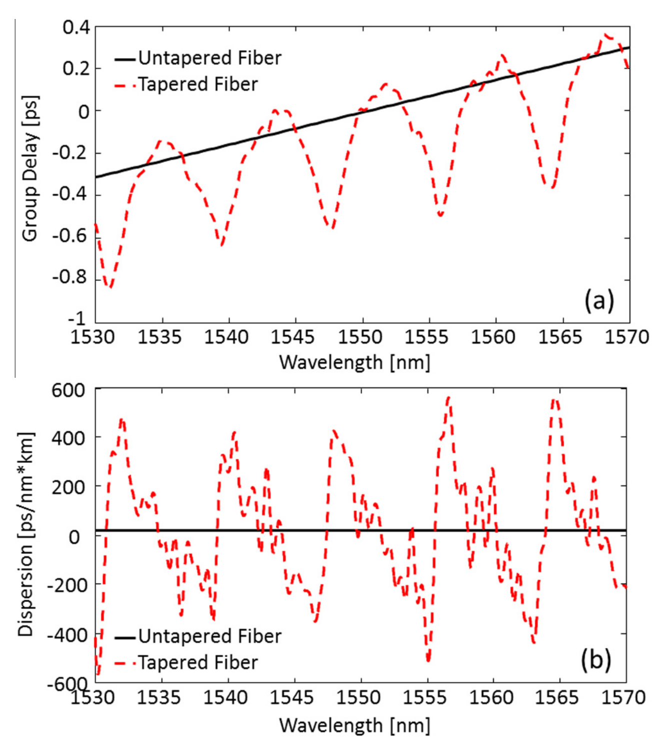

Fig. 3. (a) Group delay and (b) chromatic dispersion of a single mode standard fiber with and without tapering it.